GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. G-35-503 (P5042-0A0) GTRC/GIT DATE 11 / 19 / 85

Project Director: Dr. C. G. Justus School/Lab Geophysical Sciences

Sponsor: Universities Space Research Association

Type Agreement: Letter dated 11/7/85 (Under Gov't. Prime NAS8-36400/1)

Award Period: From 9/10/85 To 12/10/85 (Performance) 1/9/86 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$ 50,402	$ 50,402
Funded:	$ 50,402	$ 50,402

Cost Sharing Amount: $ None Cost Sharing No: N/A

Title: Improvements in the Global Reference Atmospheric Model

ADMINISTRATIVE DATA

OCA Contact Brian Lindberg x-4820

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Defense Priority Rating: N/A Military Security Classification: N/A

(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached N/A Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with None proposed or anticipated.

COMMENTS:

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FORM OCA 65:285

GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

SR206

Date 3/7/86

Project No. G-35-503(P5042-0A0) — School/Lab Geo.Sci.

Includes Subproject No.(s)

Project Director(s) Dr. C.G. Justus — GTRC / GIT

Sponsor Universities Space Research Association

Title Improvements In The Global Reference Atmospheric Model

Effective Completion Date: 12/10/85 (Performance) 1/9/86 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [x] Final Invoice or Final Fiscal Report ASAP
- [ ] Closing Documents
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

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FINAL REPORT

IMPROVEMENTS IN THE GLOBAL REFERENCE ATMOSPHERIC MODEL

By

C. G. Justus, F. N. Alyea, and D. M. Cunnold

Prepared for

UNIVERSITIES SPACE RESEARCH ASSOCIATION
BOULDER, COLORADO 80302

and

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

Under

Project P5042-OAO
(Government Prime NAS8-36400/1)

January 1986

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF GEOPHYSICAL SCIENCES
ATLANTA, GEORGIA 30332

1986

IMPROVEMENTS IN THE GLOBAL REFERENCE ATMOSPHERIC MODEL

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Abstract

Revised perturbation magnitudes for pressure, density and temperature for use in the Global Reference Atmospheric Model (GRAM) in the height range 65-90 km are presented. A new parameter is also developed which allows selection of larger or smaller perturbation magnitudes for simulation of unusually disturbed or unusually quiescent conditions. Changes for the GRAM source code are given which provide corrections in setting up the low altitude, low latitude data grids as well as other problems recently encountered by GRAM users.

IMPROVEMENTS IN THE GLOBAL REFERENCE ATMOSPHERIC MODEL

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Background

The Global Reference Atmospheric Model (GRAM), developed at Georgia Tech, and now in version MOD 3 (Justus et al., 1980), is composed of three main data sources for monthly mean values over the height range which it covers. Between the surface and 25 km altitude, it uses NASA's four-dimensional worldwide data set, developed by Environmental Research and Technology (Speigler and Fowler, 1972), for height, latitude, longitude, and monthly-mean parameters. A middle-atmosphere section (25-90 km), is based around the Groves (1971) mean model, which includes latitude, height and monthly variation, with modifications to include longitude variations. These longitude variations are based on Meteorological Rocket Network data from 20 to 52 km, and an empirical vertical extrapolation technique (Graves, 1973) between 52 and 90 km. Above 90 km, the mean conditions are specified by the Jacchia (1970) model which is based on an empirical fit to satellite orbital drag observations.

For use in simulating perturbations along launch or reentry trajectories, GRAM includes data for both large scale (e.g., synoptic, planetary wave, diurnal, tidal) and small scale (e.g., gravity wave) variations. The magnitudes are dependent on month, latitude, and height. The perturbation values along a given trajectory depend on both horizontal and vertical scale values. The GRAM horizontal scale values for wind and thermodynamic properties are assumed to be equal and to depend only on height (not on month, latitude, or longitude). For example, the horizontal scale for the large-scale perturbations is about 1300 km, while that for the small-scale perturbations is about 80 km (at 70 km altitude). GRAM assumes different values for the vertical scales of the thermodynamic and wind quantitites for both the small-scale and the large scale perturbations. Values for the large scale are about 17 km for density and 5 km for winds at 70 km altitude. Corresponding quantities for the small-scale perturbations are about 16 km for density and 12 km for winds.

Improvements in the Random Perturbation Magnitudes

The two-scale random perturbation model used in the GRAM-Mod 3 program is described in Appendix A. For evaluation of the random perturbations it is necessary to have values of: (1) the standard deviations expected about the mean values (e.g., σ_ρ, σ_T, etc.), and (2) the magnitudes of the horizontal and vertical scales L_H and L_V (see Appendix A equations A-37 through A-39). Standard deviations and scales must be evaluated for the small-scale and the large-scale simulation components.

Because the Space Shuttle system has encountered some problems during reentry due to density perturbations near 70 km altitude, it is important that the perturbation magnitudes used in the GRAM model be as accurate as possible, especially those near this height range in which the vehicle most readily reacts to perturbations encountered on its reentry trajectory. Since the data base from which the GRAM perturbation model was developed dropped off sharply in quantity above the upper height of the Meteorological Rocket Network (i.e., above 65 km), even a limited amount of new data in this height range could considerably improve the accuracy of the model values for perturbation magnitude and scales. As recently pointed out by Walterscheid (unpublished memo, May, 1985), even a re-analysis of the existing upper air data base (e.g., by starting with an annual harmonic model for the mean atmosphere) can alter the perturbation magnitude parameters significantly in the data-sparse region above 65 km.

The random perturbation magnitudes above 65 km were originally based on root-mean-square (rms) deviations about seasonal mean values derived from rocket grenade data (Theon et al., 1972). Since this analysis erroneously includes a portion of the seasonal variance in the residuals, an approach based on a seasonal harmonic fit to the individual observations is required. For this re-analysis, all of the original rocket grenade data (Smith et al., 1964, 1966, 1967, 1968, 1969, 1970, 1971) were used from sites at Barrow, Alaska; Fort Churchill, Canada; Wallops Island, Virginia; and combined Natal/Ascension Island. Steps in the re-analysis consisted of:

(1) an annual harmonic fit to all the grenade data (using annual and semi-annual components), as illustrated in Figures 1 and 2.

(2) at each site and height, grouping the residuals from the annual harmonic fit into four approximately equal groups and evaluating a root-mean-square value for each group of residuals. This provides four estimates of σ value at four times of year (the average day of year for each residual group).

(3) fitting an annual cycle (annual component only) through the four σ values obtained in step 2. This yields, through evaluation for each month, 12 σ value estimates.

(4) calculating revised values of the coefficient of variation (σ divided by mean value) for the GRAM data base. The 12 σ values derived in step 3 were divided by the corresponding 12 monthly mean values determined for the annual-plus-semiannual harmonic fit obtained in step 1.

In fitting the rocket grenade data, results were compared by using an annual only, an annual plus semiannual, and an annual, semiannual, and terannual components. Significance tests on the residuals to these harmonic fits indicated the terannual component did not explain a statistically significant fraction of the original variance, hence only the annual plus semiannual components were used to fit the annual variation of the mean atmosphere.

A sample comparison between the original MOD 3 perturbation magnitudes and the new results is provided by the data in Figures 3 and 4. Figure 3 is for density standard deviation at 70 km altitude, 70° latitude. This figure indicates substantial reduction in σ_ρ at all months (except February at this particular height and latitude). Complete data on the new σ_ρ, σ_T and σ_P values are given in Table 1. Original values are listed in Appendix B of the GRAM MOD 3 report. Figure 4 is for temperature standard deviations at 70 km altitude, at latitude 45°. A comparison is given in Figure 4 between the GRAM values of σ_T and those determined by a new ground-based lidar system of Chanine et al (1985). This comparison verifies that the perturbation magnitudes in the GRAM data base are reasonably consistent with those found by techniques other than the rocket grenade data on which they are based.

A New Variable Perturbation Magnitude Factor

An additional option has been incorporated into the GRAM code which allows run-time selection of a multiplicative factor to apply to the perturbation magnitudes. This allows simulations of disturbed atmospheric conditions (e.g., stratospheric warming events, strong upward gravity wave propagation) by selecting a factor greater than 1.0. Selection of a factor smaller than 1.0

would allow simulation of unusually quiescent atmospheric conditions by reducing the perturbation magnitudes below their typical values.

The new variable perturbation magnitude function (RPSCALE) is included in the code by modifications given in Appendix B. The desired value of RPSCALE is input at run time by adding its value at the end of input line 3 (initial random perturbation values). If the default RPSCALE value of 1 is desired, no input value is necessary. GRAM allows RPSCALE values within the range 0 to 2. A value of 0 gives no random perturbations; a value of 2 would give perturbations which are twice annual value.

Other modifications in the GRAM MOD 3 code, required to correct various problems reported, are also given in Appendix B. These include: avoidance of negative square roots from 4-D height range data by including absolute value, inclusion of dummy variables in all COMMON statements to insure that all declared COMMONS have the same length, corrections for errors in setting up the 4-D grid data at low latitudes (changes in GEN4D, GRID4D, and SELE4 routines), as well as other minor corrections.

Scales in the Random Perturbation Model

The horizontal and vertical scales used in the random perturbation model are based on studies by Justus and Woodrum (1972, 1973, 1975) and are described in the GRAM-MOD2 report (Justus and Hargraves, 1976).

The relations used to estimate the horizontal and vertical scale values are given in Subroutine PERTRB, lines PERT 19 through PERT 33 in the program listing given in Appendix D of the GRAM MOD 3 report (Justus et al., 1980). Values computed by these relations for the horizontal and vertical length scales are shown in Figures 5 and 6. The horizontal scales are assumed to be a function of height only (independent of latitude) while the vertical scales are assumed to vary with both height and latitude.

A brief survey of new upper atmospheric data (e.g., from the MAP program and other sources) indicates no significant changes are required in the perturbation scale values. However, a more comprehensive study is being planned.

Spectra and Gradient Simulations with the GRAM Perturbation Model

The random perturbation model is basically a one-step Markov process, with an exponential correlation function $\rho(\Delta r) = e^{-\Delta r/L}$, for spatial separation Δr. L is the integral scale

$$L = {}_0\int^{\infty} \rho(\Delta r)\ d\ (\Delta r). \qquad (1)$$

Spectra consistent with this correlation function would be of the form (Lumley and Panofsky, 1964)

$$kF(k)/\sigma^2 = (kL/\pi)/(1 + k^2L^2) \qquad (2)$$

for scalar quantities (density, temperature, etc.) and for the longitudinal spectra of vector quantities (wind components). For the transverse spectra of vector components, the spectrum would be

$$kF(k)/\sigma^2 = (kL/2\pi)(1 + 3k^2L^2)/(1 + k^2L^2)^2. \qquad (3)$$

Both of these spectra vary as $F(k) \propto k^{-2}$ at large values of k ($kL >> 1$), i.e., for small scales of separation.

Figure 7 shows a comparison between the vertical spectrum of horizontal wind (equation 3) evaluated from the GRAM perturbation model and spectra presented recently by Van Zandt (1985). For wavelengths less than about 1 km (wave numbers greater than 10^{-3} cycles/m) the observed spectra are consistent with $F(k) \propto k^{-3}$, a characteristic of the spectrum of a saturated field of gravity waves (Smith et al., 1985).

Figure 8 illustrates an application of the GRAM perturbation model in simulating vertical density gradients by vertical density profiles (at the latitude-longitude of Eilson AFB, Alaska in January). Vertical steps of 1 km or 0.25 km were used. Larger density gradient ($\Delta\rho/\Delta Z$) values are evident with the 0.25 km spacing.

For vertical displacement, ΔZ, the Markov model used in the GRAM perturbation routine produces rms gradients which, in the limit $\Delta Z/L << 1$, are given by

$$(\Delta\rho/\Delta Z)_{rms} = \sigma_\rho[2(1 - e^{-\Delta Z/L})]^{1/2}/\Delta Z, \qquad (4)$$

which, for $\Delta Z/L << 1$ approximates to

$$(\Delta\rho/\Delta Z)_{rms} = \sigma_\rho(2/\Delta Z L)^{1/2}. \qquad (5)$$

Thus, as the vertical step ΔZ is decreased in the Markov simulation, the rms density (or other parameter) gradient will increase inversely as the square root of ΔZ. This is the phenomenon illustrated in Figure 8.

Comparison of the spectra in Figure 7 suggests that, if the vertical spacing is 1 km or greater the perturbation results will be consistent with observed spectral magnitudes and gradients. However, the fact that the model spectrum $\propto k^{-2}$ versus the observed spectrum $\propto k^{-3}$ for large k (small displacement) suggests that unrealistic gradients and spectral magnitudes might result for vertical separation of less than 1 km. For this reason it is recommended that simulations be done with GRAM with a minimum vertical spacing of 1 km. If simulations are desired along a trajectory at closer intervals than 1 km in the vertical, these can be evaluated by interpolation between GRAM-simulated values at the 1 km vertical spacing limit.

Suggestions for Further Improvement

Figures 9-12 give examples of the comparison of monthly mean temperature and density in the GRAM model (from Groves (1971)) with the new satellite data (Barnett and Corney, 1985) and rocket results (Koshelkov, 1985) obtained in the MAP program. Since southern hemisphere means between 25 and 90 km are assumed to be the same as northern hemisphere means displaced by six months, the December and June GRAM data in Figures 9 and 10 are simply reflections about the equator. At 70-90 km, the mean temperature in the GRAM model appears to be significantly low above 60° latitude. Density discrepancies of about 10% also appear between the GRAM mean densities and the satellite results at 70 km.

In addition to monthly mean values, Barnett and Corney (1985) also have derived mean amplitudes and phases of wavenumber 1 and 2 perturbations about the mean. These correspond to the "stationary perturbations" of the GRAM model. Data in Figures 13-16 show that the GRAM stationary perturbations are consistent in both amplitude and phase with the Barnett data at 30° latitude. At 70° latitude, although the amplitudes are consistent, the phases are significantly different between the GRAM and Barnett data.

Further analysis of the MAP results is planned. This major new data source, together with other new data (e.g., Groves, 1985), could serve to provide significant future improvements in the GRAM model: (1) New monthly mean values, distinct in southern and northern hemispheres, (2) revised stationary perturbation values, expressed in wave number terms rather than in grid spacing as in the current GRAM model, (3) further revision in the random perturbation magnitudes and scales.

Comparisons are also planned between GRAM and three-dimensional upper atmospheric global circulation model simulations. This will allow better analysis of the empirical variations in GRAM with those which are consistent with the upper atmospheric physical processes simulated by the 3-D model.

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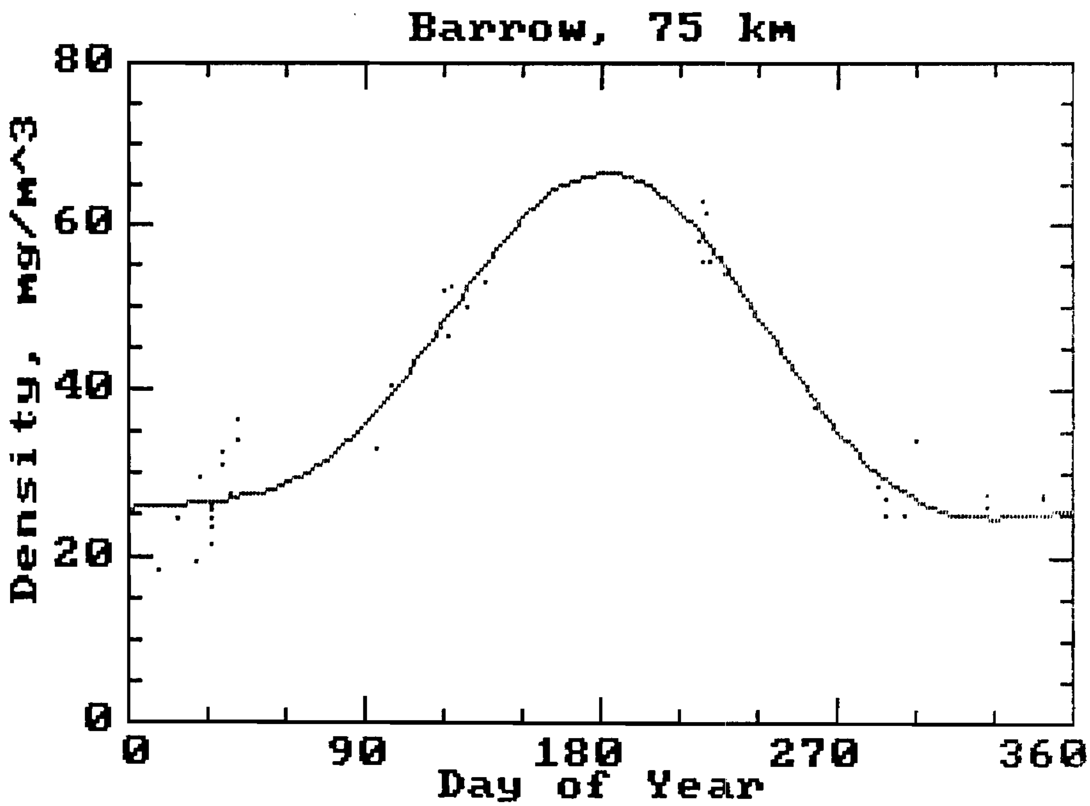

Figure 1: Sample fit of annual plus semiannual components to Rocket Grenade Density Data (Barrow, 75 km).

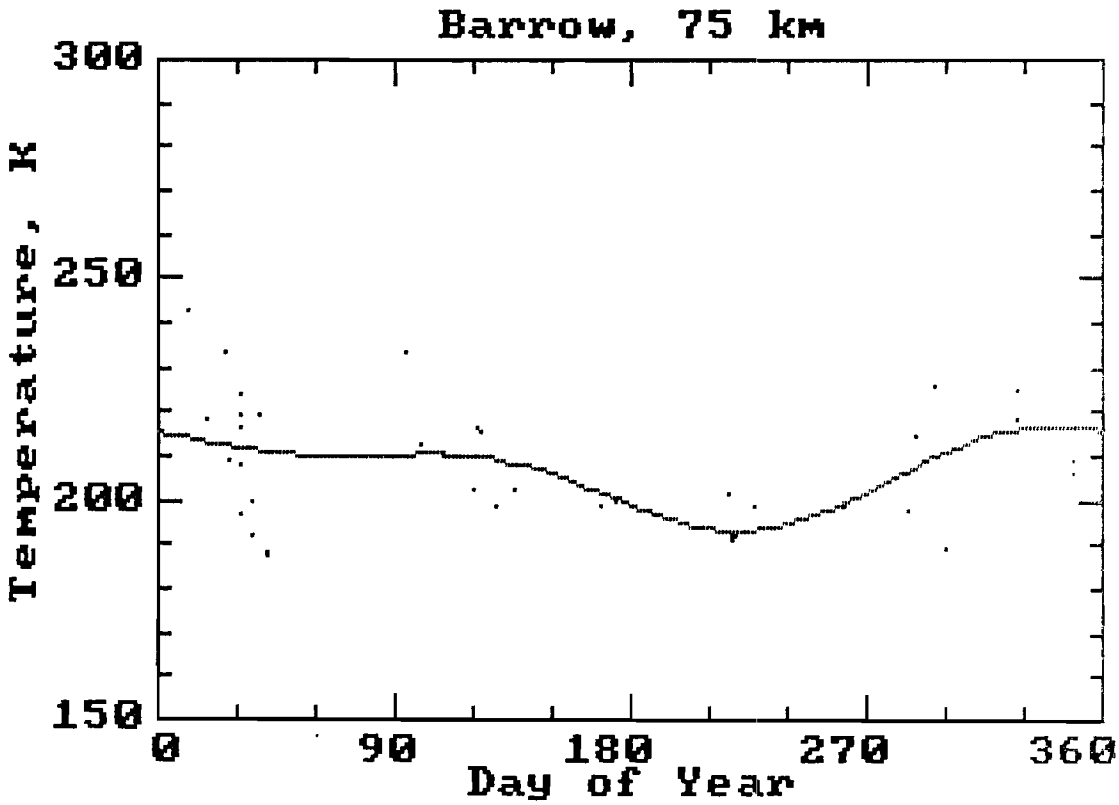

Figure 2: As in Figure 1 for Temperature.

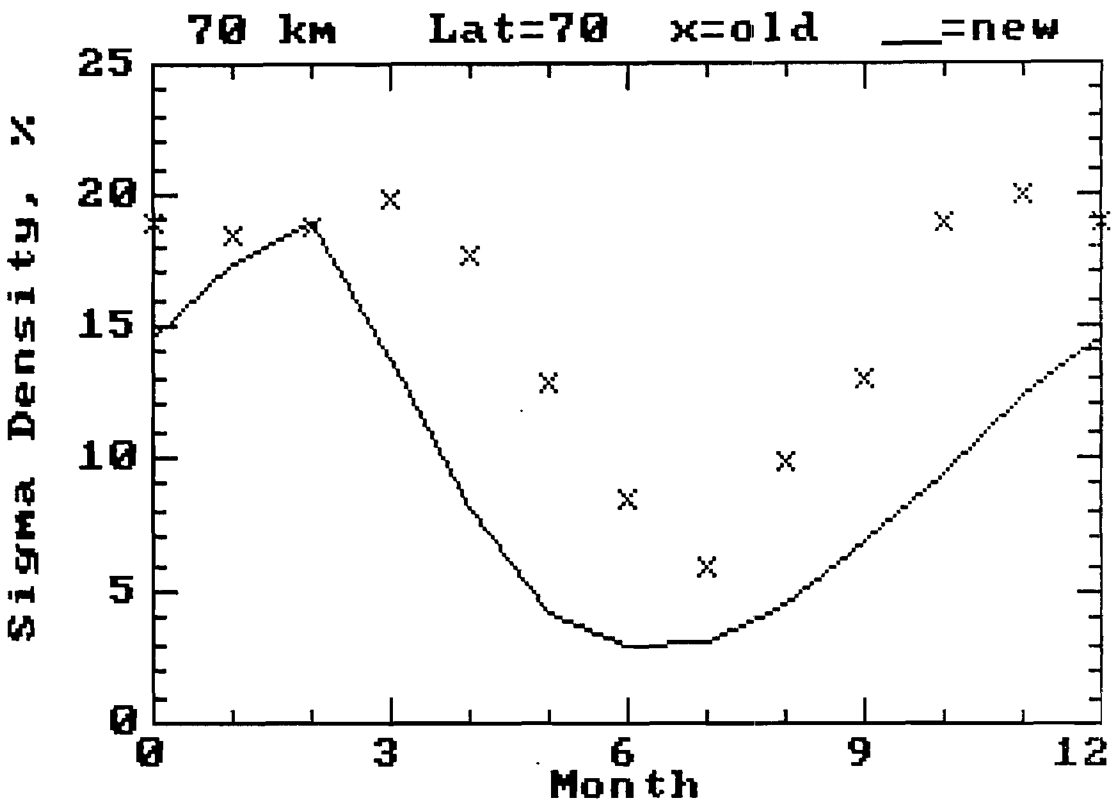

Figure 3: New (solid line) versus old (X's) values of σ_{ρ}/ρ (density perturbation magnitude) at height 70 km, latitude 70°.

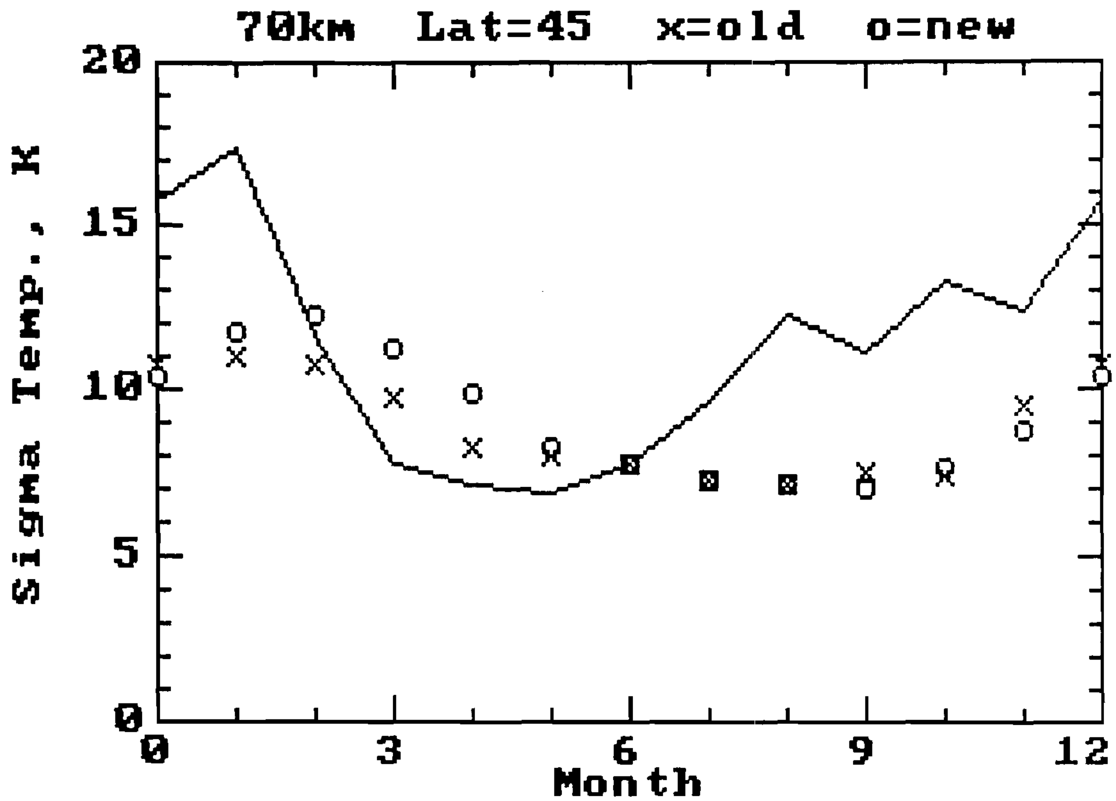

Figure 4: New (O's) and old (X's) values of $\sigma_T/\bar{T}$ at height 70 km, latitude 45°. Lidar data of Chanine (1985) are shown as the solid line.

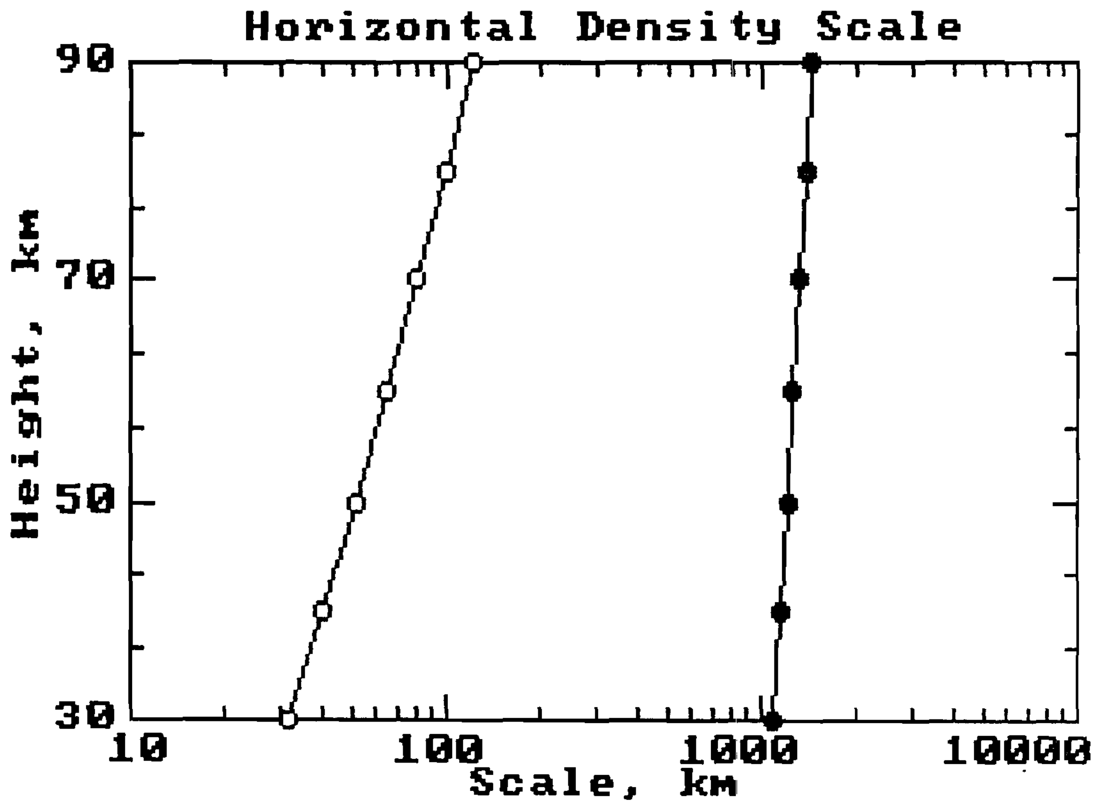

Figure 5: GRAM model horizontal large (solid dot) and small (open circle) scale density scale values for heights 30-90 km.

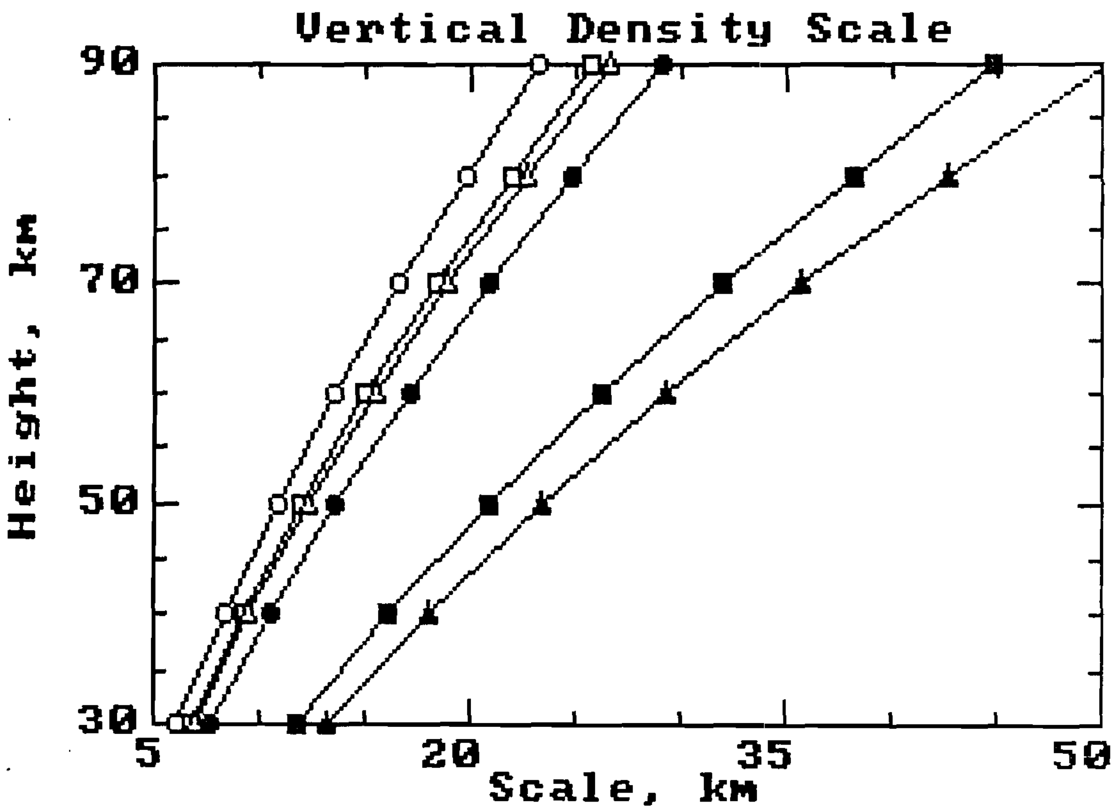

Figure 6: GRAM model vertical large (solid symbol) and small (open symbol) density scale values for latitudes 10° (circles), 50° (squares) and 90° (triangles).

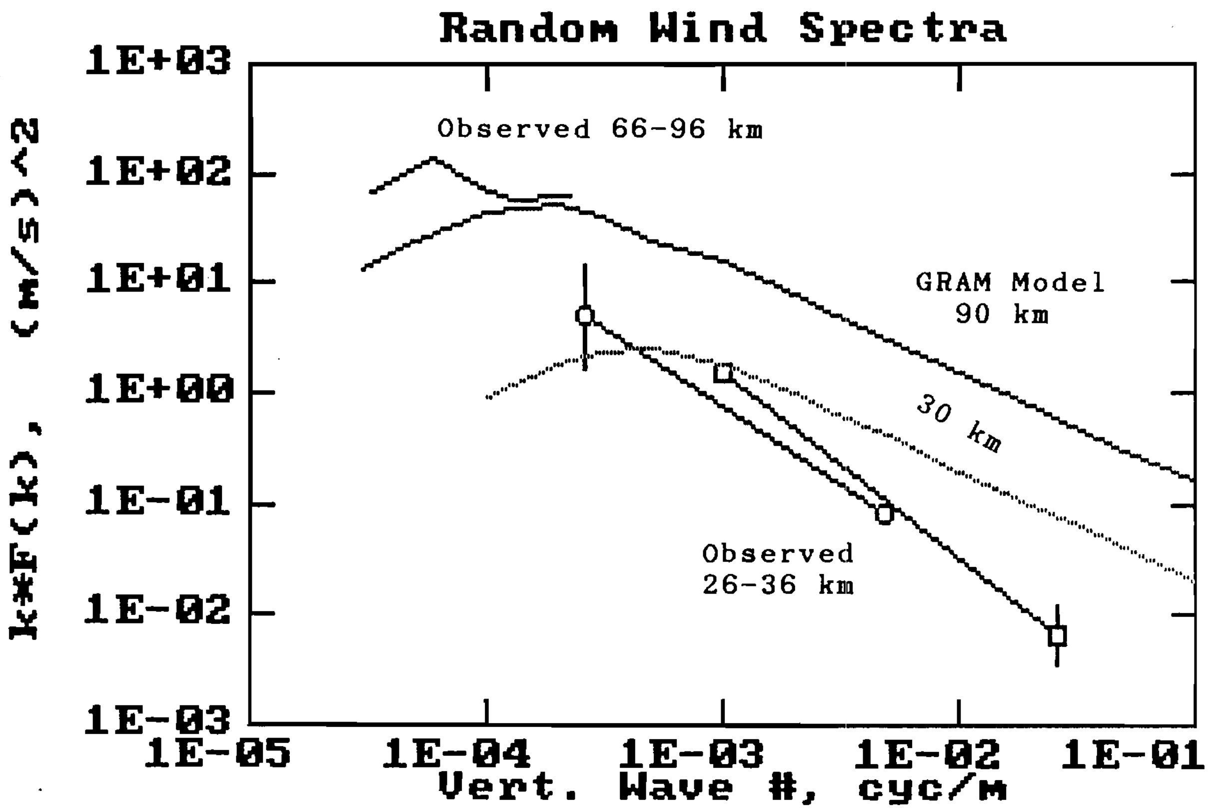

Figure 7: Comparison of GRAM model wind spectra with observations of Van Zandt (1985).

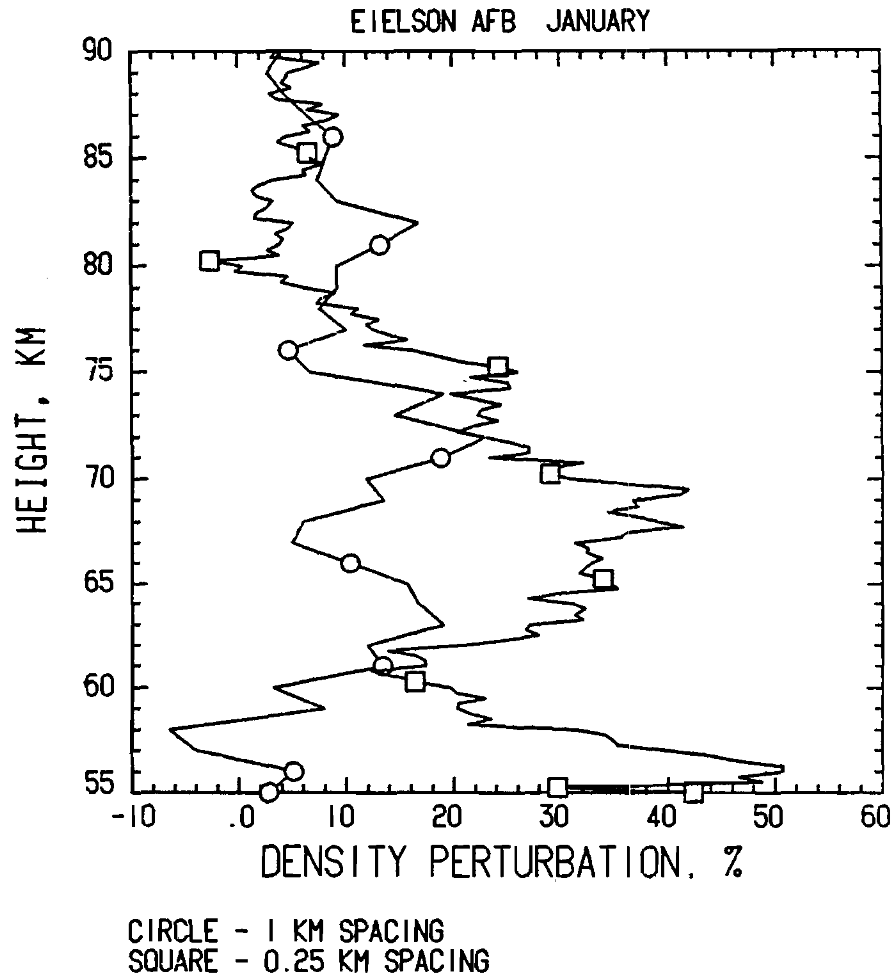

Figure 8: Sample vertical density perturbation profile simulation with GRAM at 1 km (circles) and 0.25 km (squares) spacing.

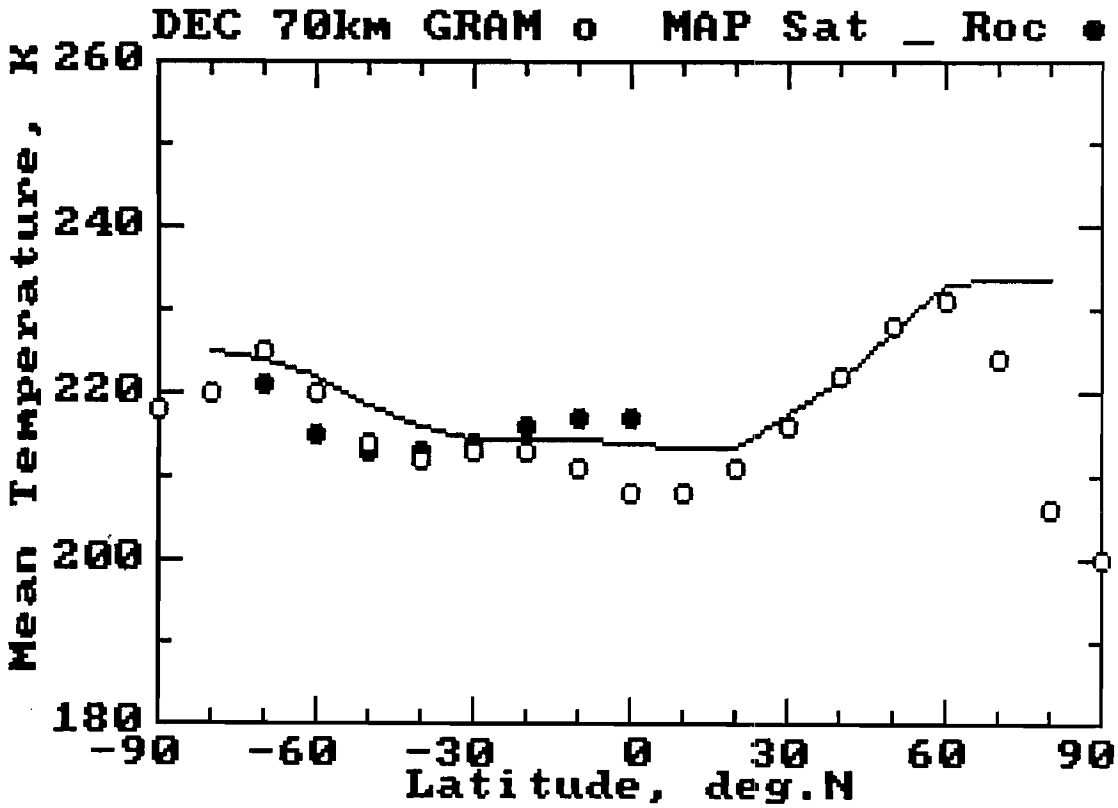

Figure 9: Comparison of GRAM model mean temperature for December, 70 km, with satellite data of Barnett and Corney (1985) and southern hemisphere rocket data by Koshelkov (1985).

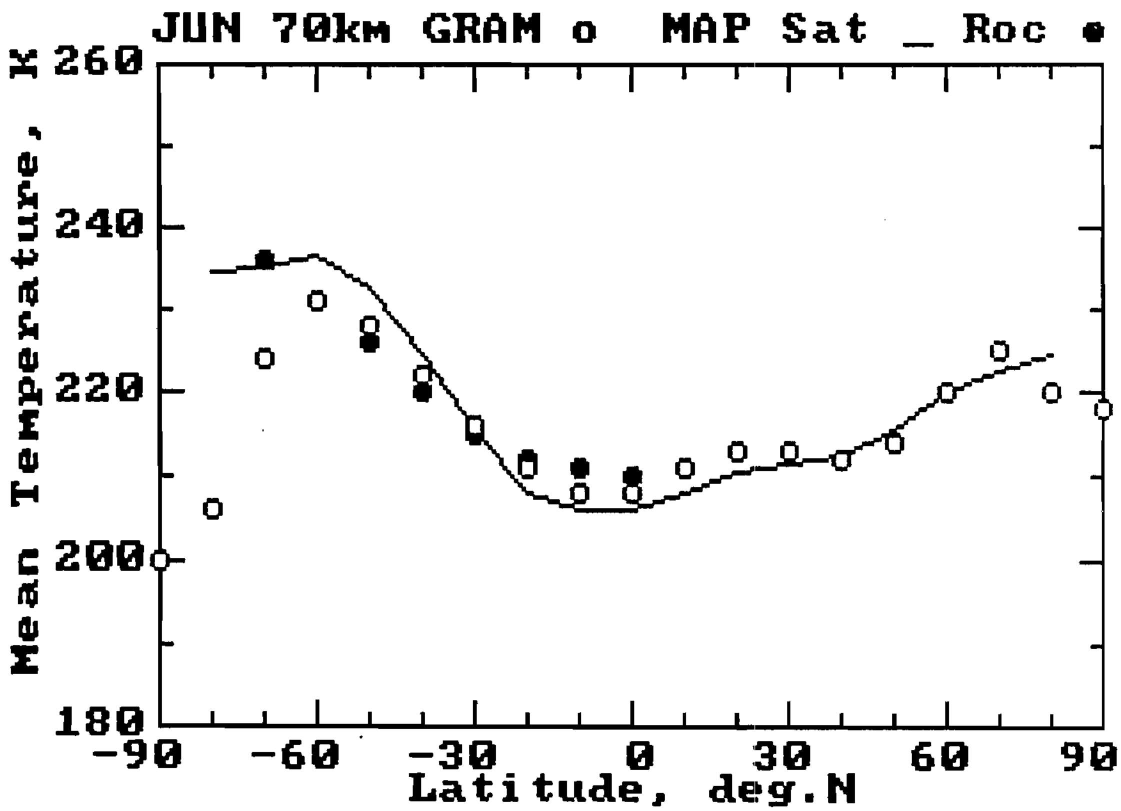

Figure 10: As in Figure 9 for June.

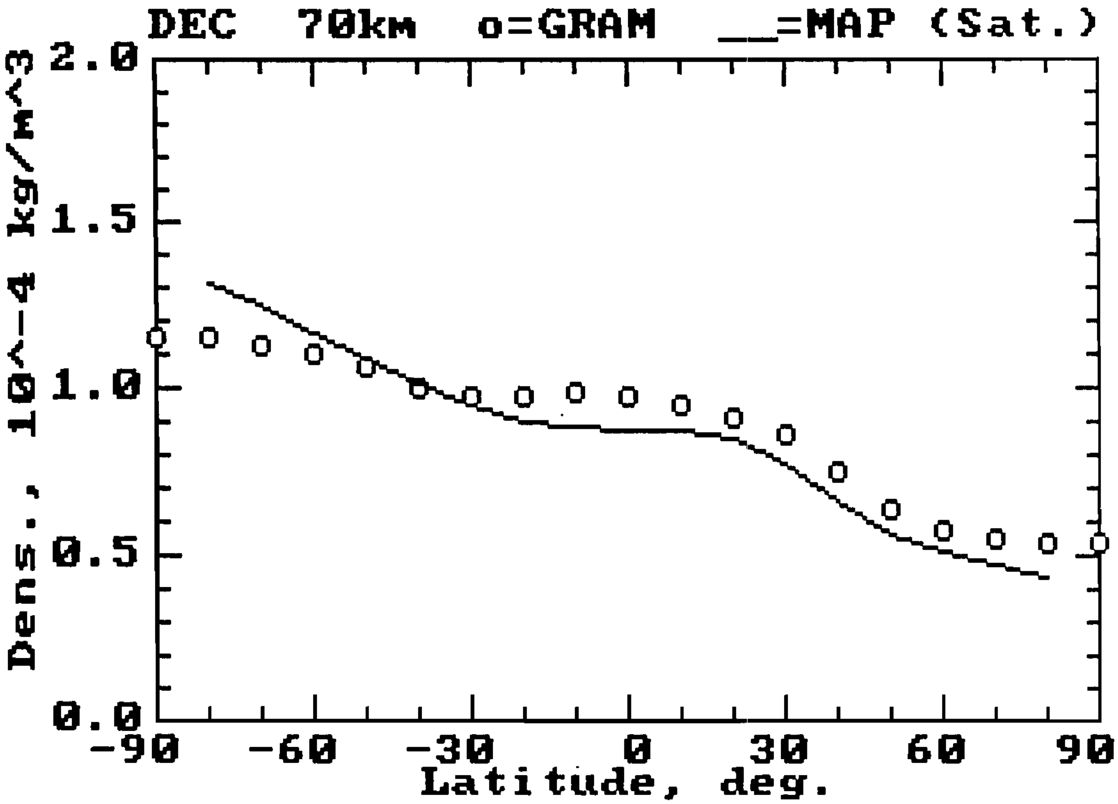

Figure 11: As in Figure 9 for Density.

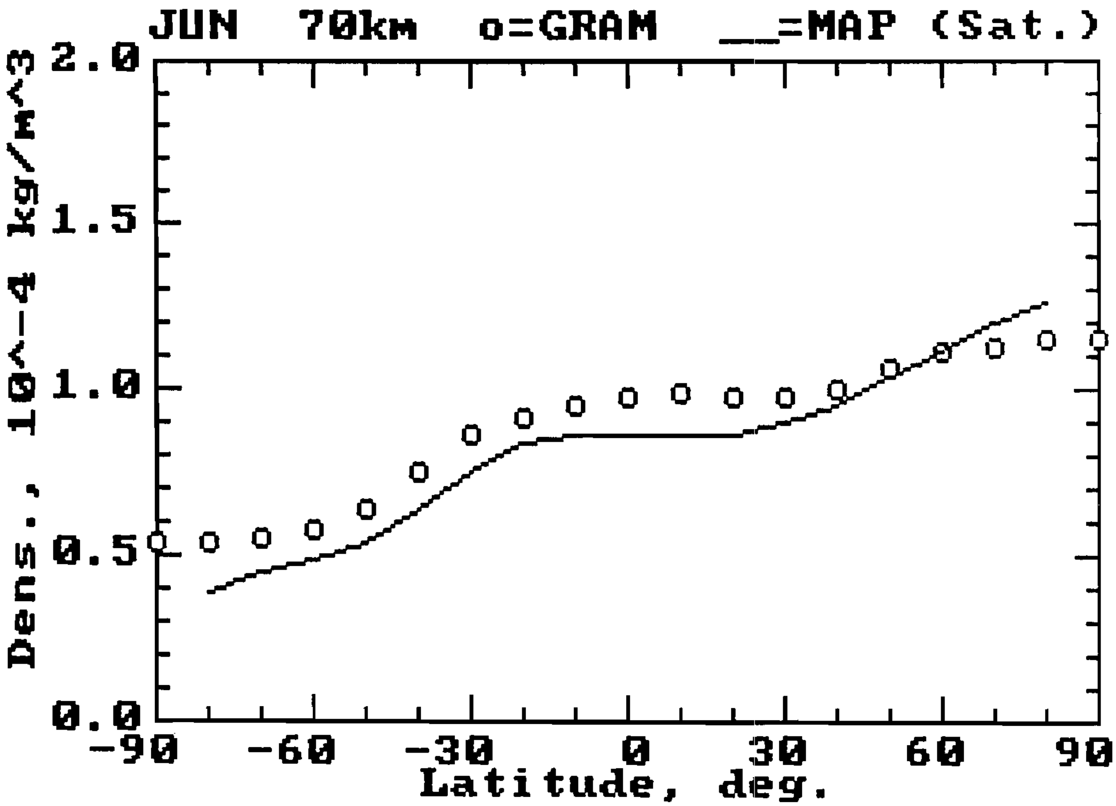

Figure 12: As in Figure 9 for June Density.

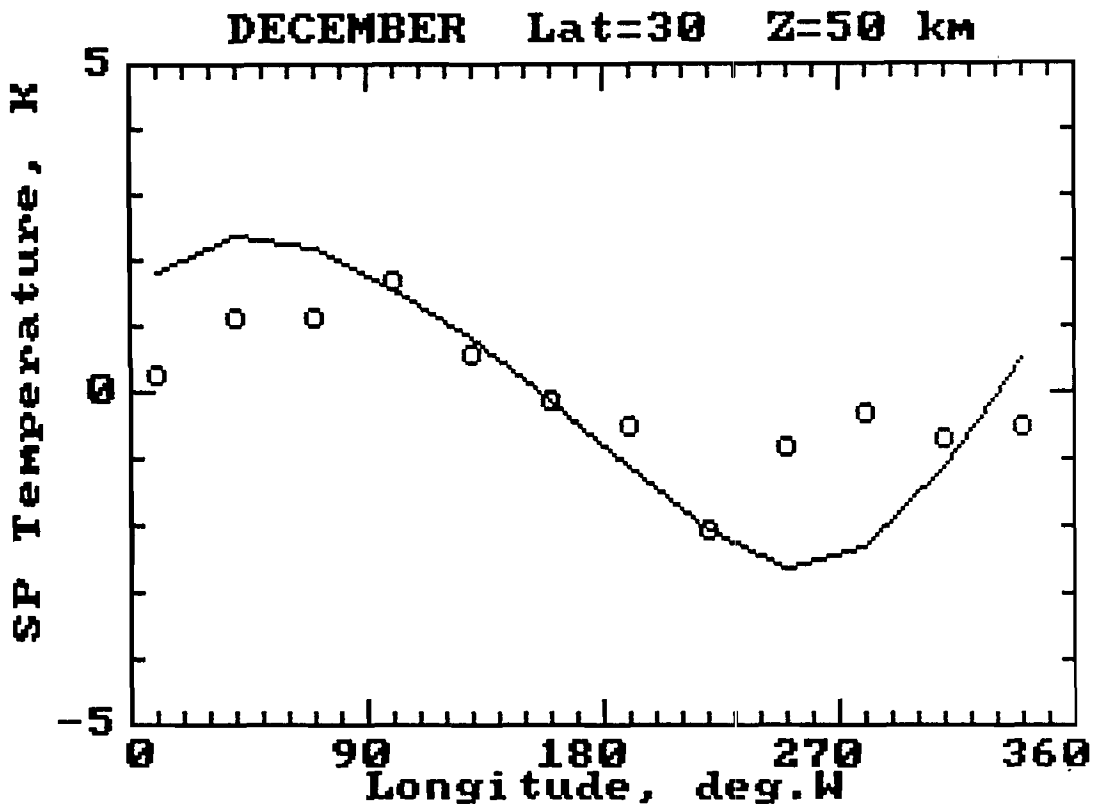

Figure 13: Comparison of GRAM model stationary perturbation values for December at latitude 30°, height 50 km with wave-1 plus wave-2 values for satellite data (Barnett and Corney, 1985).

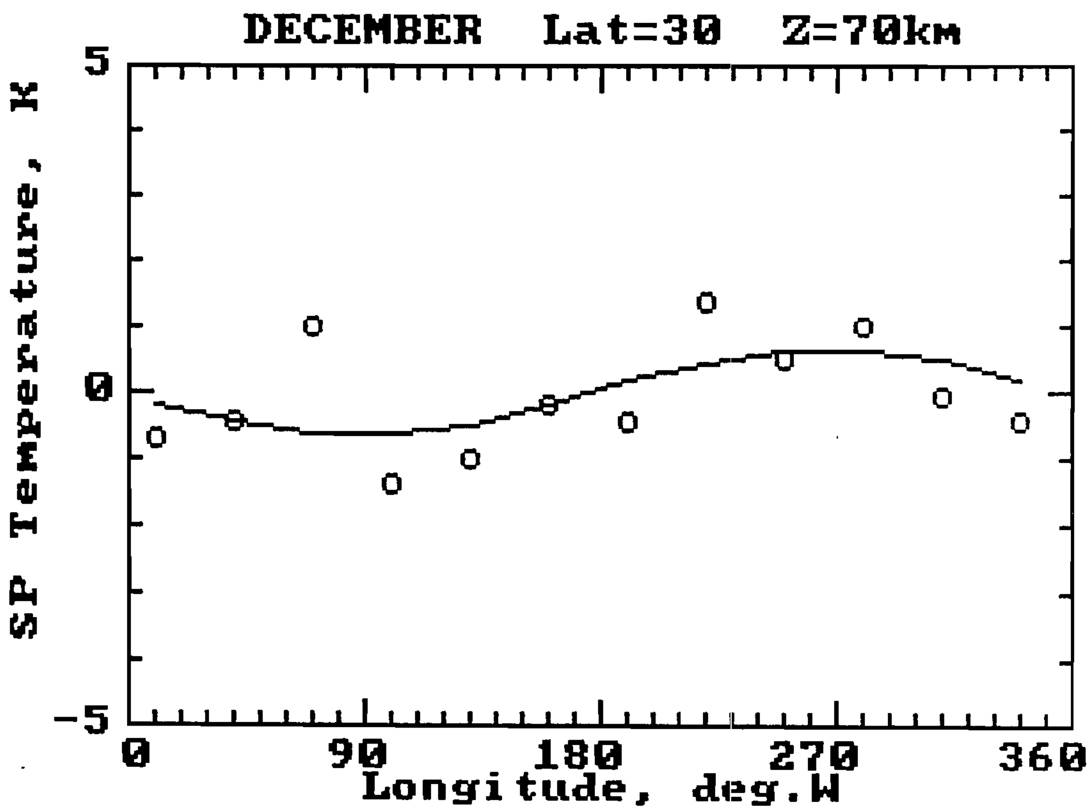

Figure 14: As in Figure 13 for height 70 km.

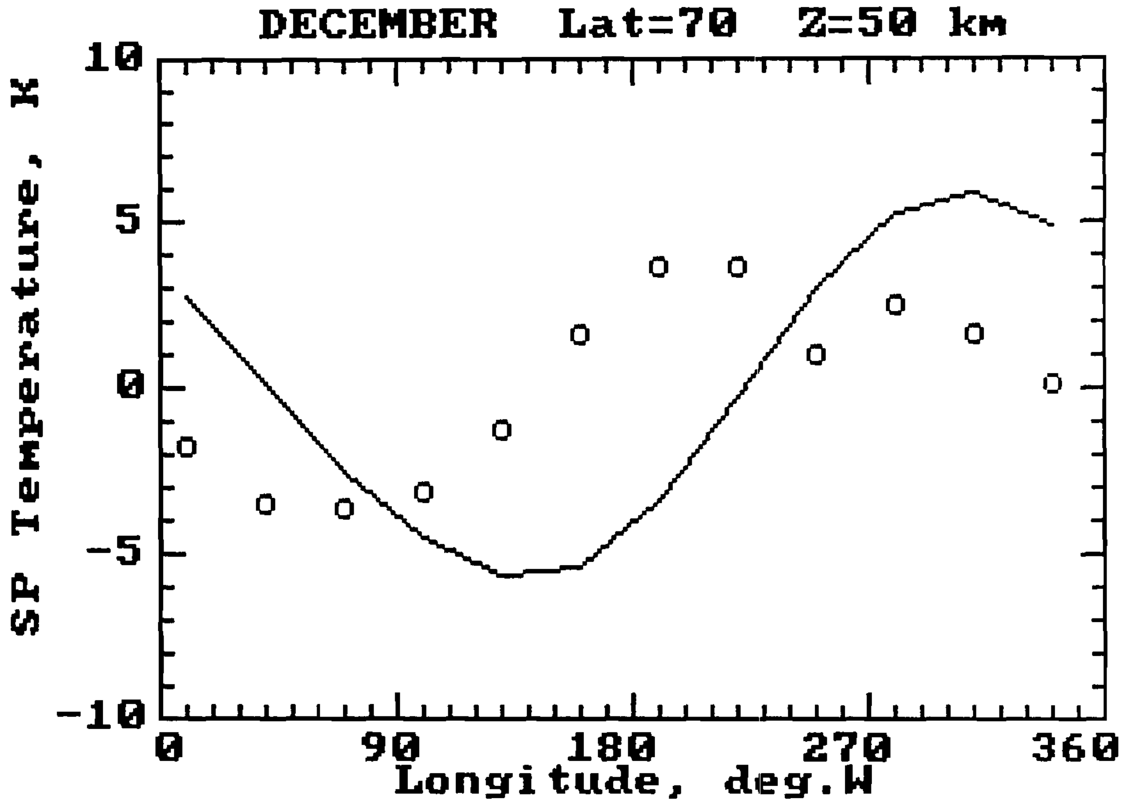

Figure 15: As in Figure 13 for latitude 70°, height 50 km.

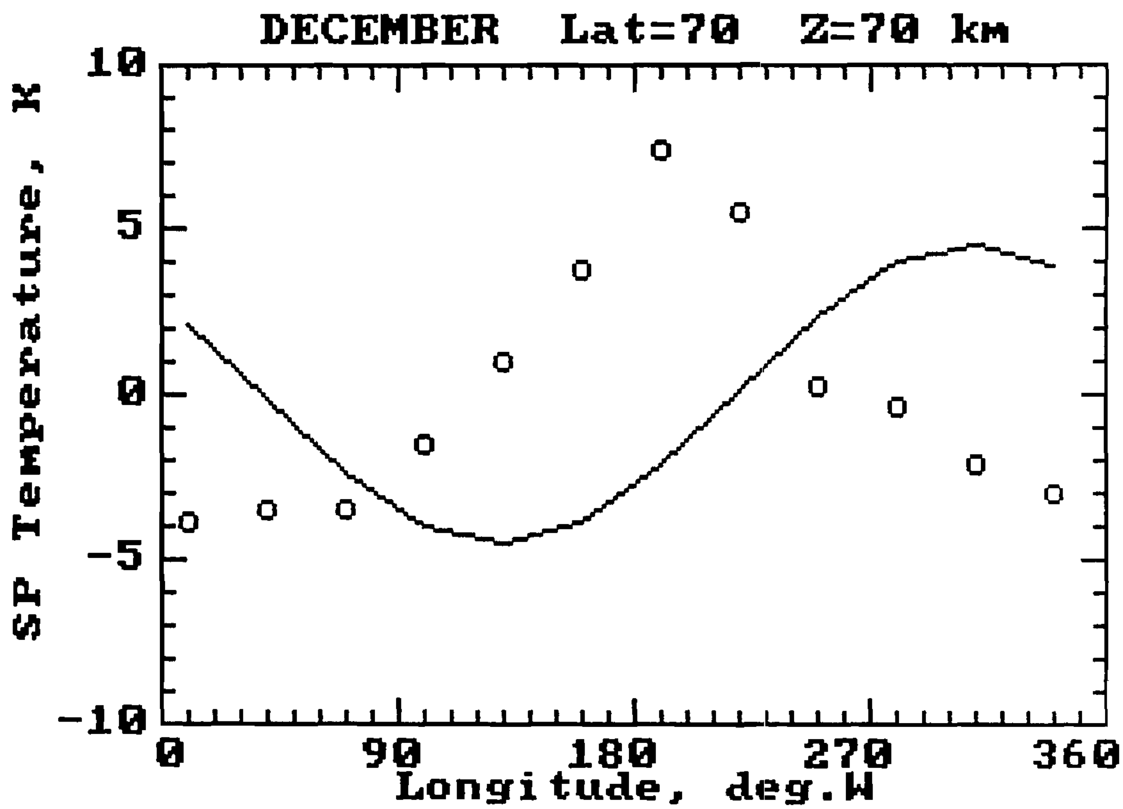

Figure 16: As in Figure 13 for latitude 70°, height 70 km.

Table 1. Revisions in the Code R, Random Perturbation Values for the SCIDAT Data Tape. Values are per mill (percent x 10), for heights between 65 and 90 km, at latitudes 10 through 90. All other values remain unchanged from the original SCIDAT data values listed in the GRAM MOD-3 report (Justus et al., 1980).

			Pressure					Density					Temperature				
Code	MON	HGT	10	30	50	70	90	10	30	50	70	90	10	30	50	70	90
R	1	65	29	53	115	169	191	47	66	130	189	212	22	33	43	50	52
R	1	70	28	66	111	145	157	37	70	127	174	193	31	47	54	57	58
R	1	75	43	80	105	118	123	40	78	123	156	169	42	54	63	68	70
R	1	80	69	100	103	97	94	56	93	121	138	144	57	64	72	77	79
R	1	85	106	118	102	83	74	83	115	121	118	116	73	70	80	91	96
R	1	90	158	138	101	70	58	121	137	121	100	92	86	77	90	104	111
R	2	65	38	60	144	222	253	45	62	132	198	224	28	38	39	39	38
R	2	70	35	62	127	183	206	40	61	128	189	213	32	47	57	63	65
R	2	75	50	73	116	153	167	45	70	127	177	196	41	54	70	82	87
R	2	80	79	96	108	116	119	61	86	129	165	179	52	63	79	93	98
R	2	85	118	124	105	84	75	87	116	130	137	139	68	72	83	94	98
R	2	90	168	151	99	52	34	124	149	130	105	94	83	82	88	94	96
R	3	65	53	68	128	182	203	47	63	108	148	163	35	38	35	32	31
R	3	70	52	58	109	158	177	54	57	98	138	154	33	47	51	52	51
R	3	75	70	63	102	142	158	68	66	99	133	146	41	58	66	68	68
R	3	80	98	88	99	113	119	84	84	108	131	141	51	66	76	81	82
R	3	85	131	122	101	81	74	103	115	119	120	120	67	76	81	84	84
R	3	90	172	162	102	45	23	125	155	128	93	78	85	86	85	83	83
R	4	65	70	85	108	128	135	54	80	93	97	98	40	35	30	26	25
R	4	70	75	73	92	111	119	71	69	75	81	84	36	47	43	35	32
R	4	75	96	78	91	109	117	93	72	72	79	83	41	61	56	45	40
R	4	80	116	91	91	97	100	108	87	85	89	91	49	68	69	64	62
R	4	85	139	121	97	77	70	119	116	104	94	89	65	80	79	73	71
R	4	90	173	174	111	48	22	122	158	126	82	64	91	90	83	77	74
R	5	65	79	97	91	79	74	57	94	80	55	44	39	30	25	23	22
R	5	70	97	90	81	75	72	86	80	61	42	35	37	46	35	22	16
R	5	75	109	93	84	81	80	108	82	58	42	37	40	63	45	22	12
R	5	80	120	100	87	80	78	119	91	70	57	52	46	68	59	43	37
R	5	85	133	122	96	74	65	122	115	92	72	64	64	80	73	61	56
R	5	90	160	175	116	52	26	114	158	124	78	59	97	88	77	70	67
R	6	65	80	104	78	46	33	58	104	75	33	15	36	26	22	20	20
R	6	70	96	106	82	55	44	85	91	61	30	17	35	45	33	17	11
R	6	75	100	108	86	61	52	100	89	59	33	23	38	59	42	20	10
R	6	80	102	106	89	71	64	107	95	68	45	36	46	69	54	32	23
R	6	85	108	118	96	71	61	109	113	88	62	52	63	78	68	53	47
R	6	90	127	154	111	60	39	103	149	125	86	70	90	74	71	73	74

Table 1, continued.

Code	MON	HGT	Pressure 10	30	50	70	90	Density 10	30	50	70	90	Temperature 10	30	50	70	90
R	7	65	72	103	77	43	28	52	101	76	38	21	32	26	23	21	21
R	7	70	83	102	78	49	37	75	92	65	32	19	32	41	32	20	15
R	7	75	77	101	81	55	44	84	92	65	35	23	35	52	41	25	18
R	7	80	77	101	86	64	54	89	95	71	46	36	45	62	51	36	30
R	7	85	80	111	93	67	55	94	110	89	64	53	61	68	64	57	55
R	7	90	92	123	99	66	52	97	135	122	97	87	82	62	66	76	81
R	8	65	55	95	77	48	36	46	95	80	51	38	29	27	26	25	24
R	8	70	59	91	76	52	41	60	92	74	46	34	29	37	33	27	25
R	8	75	55	87	76	56	47	66	93	74	47	36	35	45	41	33	30
R	8	80	57	86	78	62	55	74	93	77	56	47	48	57	51	43	39
R	8	85	64	96	84	62	53	86	104	91	73	66	64	62	60	59	59
R	8	90	65	92	80	60	51	95	115	113	105	101	82	56	62	76	82
R	9	65	37	85	82	65	57	42	86	89	80	74	27	28	29	30	30
R	9	70	40	76	72	58	51	49	88	84	69	62	28	32	34	34	35
R	9	75	42	70	67	57	52	56	88	83	68	61	36	40	42	42	42
R	9	80	51	73	69	59	54	69	89	84	74	70	52	53	51	50	49
R	9	85	65	82	71	55	48	87	95	93	90	88	72	60	60	62	63
R	9	90	77	79	68	56	52	108	97	98	102	104	99	65	67	80	85
R	10	65	24	69	79	76	73	42	81	99	107	109	25	27	34	41	43
R	10	70	28	65	71	66	63	41	82	94	94	93	29	34	37	39	39
R	10	75	37	67	68	60	56	49	82	90	88	86	41	45	43	40	39
R	10	80	52	71	67	59	54	64	87	90	87	86	58	55	52	51	50
R	10	85	71	71	65	60	57	86	86	90	95	97	78	62	62	66	69
R	10	90	98	79	69	64	62	113	88	88	95	99	114	77	76	86	91
R	11	65	21	57	80	93	97	43	74	111	139	149	22	27	38	47	51
R	11	70	24	62	76	80	80	37	77	106	123	129	30	38	41	43	43
R	11	75	36	69	74	69	66	42	79	100	109	112	42	49	47	43	42
R	11	80	55	80	75	63	57	57	88	97	98	98	59	59	57	54	54
R	11	85	81	85	75	64	60	83	94	96	95	94	78	65	67	73	76
R	11	90	121	99	82	71	67	116	103	95	90	89	110	78	82	95	101
R	12	65	24	52	89	118	129	46	70	121	165	182	21	29	41	51	55
R	12	70	24	63	87	100	104	36	74	115	145	156	31	43	47	48	48
R	12	75	38	75	84	83	81	40	81	109	125	130	43	52	53	51	50
R	12	80	62	91	87	74	68	56	92	105	108	108	59	62	62	61	61
R	12	85	92	102	90	74	68	82	105	104	96	92	77	68	73	82	86
R	12	90	140	120	97	79	72	118	119	105	90	85	101	77	87	104	112

APPENDIX A

THE TWO-SCALE RANDOM PERTURBATION MODEL

The original single scale perturbation model in the Global Reference Atmosphere Model (Justus et al., 1974) was evaluated by the following method: first the density perturbation ρ_2' at the new location was computed from ρ_1' the density perturbation at the previous location by the relation

$$(\rho_2'/\bar{\rho}_2) = A(\rho_1'/\bar{\rho}_1) + Br_1 \qquad (A-1)$$

where $\bar{\rho}_1$ and $\bar{\rho}_2$ are the known mean densities at the previous and new positions, A and B are determined from the required conditions, and r_1 is a random number selected from a Gaussian distribution with zero mean and unit standard deviation. The required conditions to be used in determining A and B are

$$\langle \rho_2' \rho_1' \rangle = R\, \sigma_{\rho_1} \sigma_{\rho_2} \qquad (A-2)$$

and

$$\langle (\rho_2'^2) \rangle = \sigma_{\rho_2}^{\ 2} \quad , \qquad (A-3)$$

where $\sigma_{\rho 1}$ and $\sigma_{\rho 2}$ are the known standard deviations in density at the previous and new location, and R is the known autocorrelation in density perturbations between the previous and new locations. Next (with analogous notation as in (A-1) through (A-3), the new temperature perturbation was computed by

$$(T_2'/\bar{T}_2) = C(T_1'/\bar{T}_1) + D(\rho_2'/\bar{\rho}_2) + Er_2 \tag{A-4}$$

In addition to the autocorrelation R (assumed the same for T′ and ρ′ in the original one-scale model) the cross correlation $(R_{\rho T})_2$ was also maintained (through the coefficient D in equation (A-4)). The correlation $(R_{\rho T})_2$ was determined from the known standard deviations and means by the Buell (1970) relation

$$(R_{\rho T})_2 = \frac{[(\sigma_p)_2/\bar{p}_2]^2 - [(\sigma_\rho)_2/\bar{\rho}_2]^2 - [(\sigma_T)_2/\bar{T}_2]^2}{2[(\sigma_\rho)_2/\bar{\rho}_2]\ [(\sigma_T)_2/\bar{T}_2]} \quad . \tag{A-5}$$

Once the density and temperature perturbations were evaluated, the pressure perturbation was determined via

$$(p_2'/p_2) = (\rho_2'/\bar{\rho}_2) + (T_2'/\bar{T}_2) \tag{A-6}$$

which is a first order perturbation equation from the perfect gas law. In the original single scale perturbation model, wind perturbation components u′ and v′ were assumed to be uncorrelated with each other and with the thermodynamic variables, and hence were computed by relations analagous to equation (A-1).

In the original one-scale model, only the total perturbations were considered (e.g., $\rho = \bar{\rho} + \rho'$) while in the new two scale model the perturbations are assumed to be made up of a large scale and small scale component (e.g., $\rho = \bar{\rho} + \rho_L + \rho_S$). To first order in the perturbations the state of the mean atmosphere is described by

$$\bar{p} = \bar{\rho}\ R\ \bar{T} \tag{A-7}$$

and the mean plus large scale perturbations by

$$(\bar{p} + p_L) = (\bar{\rho} + \rho_L)\ R(\bar{T} + T_L) \tag{A-8}$$

and the actual atmospheric parameters p, ρ, and T by

$$p = \rho\ R\ T \quad . \tag{A-9}$$

Division of equations (A-8) and (A-9) by $\bar{p}$ on the left and by $\bar{\rho}$ R $\bar{T}$ on the right yields, to the first order in the perturbations

$$p_L/\bar{p} = (\rho_L/\bar{\rho}) + (T_L/T) \tag{A-10}$$

$$p_S/\bar{p} = (\rho_S/\bar{\rho}) + (T_S/\bar{T}) \quad . \tag{A-11}$$

These results mean that the small scale and large scale perturbations each separately must obey the Buell triangle relationships for their magnitudes. Thus, analogous to equation (A-5), the correlation $R_{\rho LTL}$ for large scale perturbations and $R_{\rho sTs}$ for small scale perturbations are given in terms of their respective magnitudes by

$$R_{\rho_L T_L} = \frac{(\sigma_{P_L}/\bar{P})^2 - (\sigma_{\rho_L}/\bar{\rho})^2 - (\sigma_{T_L}/\bar{T})^2}{2(\sigma_{\rho_s}/\bar{\rho})(\sigma_{T_s}/\bar{T}} \qquad \text{(A-12)}$$

$$R_{\rho_s T_s} = \frac{(\sigma_{P_s}/\bar{P})^2 - (\sigma_{\rho_s}/\bar{\rho})^2 - (\sigma_{T_s}/\bar{T})^2}{2(\sigma_{\rho_s}/\bar{\rho})(\sigma_{T_s}/\bar{T})} \qquad \text{(A-13)}$$

The large and small scale components are assumed to be independent so correlations such as $R_{\rho sTL}$, $R_{\rho LTs}$ etc. are taken to be zero.

The perturbations ρ_{L2} and ρ_{s2} at the new position are thus computed from the known perturbations ρ_{L1} and ρ_{s1} at the previous position by relations analogous to equation (A-1)

$$(\rho_{L_2}/\rho) = A_L(\rho_{L_1}/\rho_1) + B_L r_{L_1} \qquad \text{(A-14)}$$

$$(\rho_{s_2}/\bar{\rho}) = A_s(\rho_{s_1}/\bar{\rho}_1) + B_s r_{s_1} \qquad \text{(A-15)}$$

where A_L, B_L, A_s and B_s can each be determined (as before) from the conditions

$$\langle \rho_{L_2} \rho_{L_1} \rangle = R_L(\rho)\, \sigma_{\rho L_2}\, \sigma_{\rho L_1} \qquad \text{(A-16)}$$

$$\langle \rho_{L_2}^{\,2} \rangle = \sigma_{\rho L_2}^{\,2} \qquad \text{(A-17)}$$

$$\langle \rho_{s_2}\, \rho_{s_1} \rangle = R_s(\rho)\, \sigma_{\rho s_2}\, \sigma_{\rho s_1} \qquad \text{(A-18)}$$

$$\langle \rho_{s_2}^{\,2} \rangle = \sigma_{\rho s_2}^{\,2} \qquad \text{(A-19)}$$

where the density autocorrelations $R_L(\rho)$ and $R_s(\rho)$ are determined from the known horizontal and vertical scale of the large scale and small scale perturbations (see equations (A-37)-(A-39), following). Similarly, the temperature perturbations are computed (analogous to equation A-4) by

$$(T_{L_2}/T_2) = C_L(T_{L_1}/T_1) + D_L(\rho_{L_2}/\rho_2) + E_L r_{L_2} \qquad \text{(A-20)}$$

$$(T_{s_2}/\bar{T}_2) = C_s(T_{a_1}/\bar{T}_1) + D_s(\rho_{s_2}/\bar{\rho}_2) + E_s r_{s_2} \qquad \text{(A-21)}$$

where again D_L and D_s are determined by the required cross correlations $R_{\rho sTs}$ and $R_{\rho LTL}$ at the new position, as computed from equations (A-12) and (A-13). Once the density and temperature perturbations are computed, the pressure perturbations are evaluated from equations (A-10) and (A-11).

A further addition to the new model has been brought about by empirically evaluated correlations R_{uLvL}, R_{usvs}, $R_{uL\rho L}$, and $R_{us\rho s}$. The new method of evaluating the velocity perturbation components is somewhat analogous to that employed for the temperature component. The equations used are

$$u_{L_2} = F_L u_{L_1} + G_L \rho_{L_2} + H_L r_{u_L} \quad \text{(A-22)}$$

$$u_{s_2} = F_s u_{s_1} + G_s \rho_{s_2} + H_s r_{u_s} \quad \text{(A-23)}$$

$$v_{L_2} = I_L v_{L_1} + J_L u_{L_2} + K_L r_{v_L} \quad \text{(A-24)}$$

$$v_{s_2} = I_s v_{s_1} + J_s u_{s_2} + K_s r_{v_s} \quad \text{(A-25)}$$

where the coefficients G_L and G_s are determined from the newly evaluated correlations $R_{uL\rho L}$ and $R_{us\rho s}$, and the coefficients J_L and J_s are evaluated from the correlations R_{uLvL} and R_{usvs}.

For evaluation of the coefficients C, D, and E in (A-20) and (A-21), and the coefficients F through K in (A-22) through (A-25), these equations are successively multiplied through by the perturbation quantities on the righthand side (see Appendix B in Justus et al. (1974)). The relations thus established for the coefficients A through K (with analogous equations for both large scale A_L - K_L and small scale A_s - K_s) are

$$A = R(\rho)\ \sigma_{\rho_1}/\sigma_{\rho_1} \quad \text{(A-26)}$$

$$B = \sigma_{\rho_2}[1 - R^2(\rho)]^{1/2} \quad \text{(A-27)}$$

$$C = (\sigma_{T_2}/\sigma_{T_1})\ \{[R(T) - R(\rho)\ R_{T_2\rho_2}\ R_{T_1\rho_1}]/ \quad [1 - R^2(\rho)\ R^2_{T_1\rho_1}]\} \tag{A-28}$$

$$D = [R(T)\ \sigma_{T_2} - C\sigma_{T_1}]/A\ R_{T_1\rho_1}\ \sigma_{\rho_1}) \tag{A-29}$$

$$E = \{\sigma^2_{T_2} - C^2\ \sigma_{T_1}^{\ 2} - D^2\sigma_{\rho_2}^{\ 2} - \quad 2\ C\ D\ R\ (\rho)\ R_{T_1\rho_1}\ \sigma_{T_1}\ \sigma_{\rho_2}]^{1/2} \tag{A-30}$$

$$F = (\sigma_{u_2}/\sigma_{u_1})\ \{[R(u) - R(\rho)\ R_{u_2\rho_2}\ R_{u_1\rho_1}]/ \quad [1 - R^2(\rho)\ R^2_{u_1\rho_1}]\} \tag{A-31}$$

$$G = (R(u)\ \sigma_{u_2} - F\ \sigma_{u_1}]/[R(\rho)\ R_{u_1\rho_1}\ \sigma_{\rho_2}] \tag{A-32}$$

$$H = [\sigma_{u_2}^{\ 2} - F^2\ \sigma_{u_1}^{\ 2} - G^2\ \sigma_{\rho_2}^{\ 2} - \quad 2\ F\ G\ R\ (\rho)R_{u_1\rho_1}\ \sigma_{\rho_2}\ \sigma_{u_1}]^{1/2} \tag{A-33}$$

$$I = (\sigma_{v_2}/\sigma_{v_1})\ \{[R(v) - R(\rho)\ R_{v_2\rho_2}\ R_{v_1\rho_1}]/ \quad [1 - R^2(\rho)\ R_{v_1\rho_1}]\} \tag{A-34}$$

$$J = [R(v)\ \sigma_{v_2} - I\ \sigma_{v_1}]/[R(\rho)\ R_{v_1\rho_1}\ \sigma_{\rho_2}] \tag{A-35}$$

$$K = [\sigma_{v_2}^{\,2} - I^2 \sigma_{v_1}^{\,2} - J^2 \sigma_{\rho_2}^{\,2} -$$

$$2\, I\, J\, R\,(\rho)\, R_{v_1 \rho_1}\, s_{\rho_2}\, \sigma_{v_1}]^{1/2} \qquad \text{(A-36)}$$

where the autocorrelations of density $R\,(\rho)$, temperature $R(T)$ and wind $R(u)$ ($R(u)$ and $R(v)$ are assumed equal), are determined from the horizontal and vertical scales $L_{Z\rho}$, $L_{H\rho}$, L_{ZT}, L_{HT}, L_{Zu}, and L_{Hu} by the relations

$$R(\rho) = \exp\{-[(\Delta x^2 + \Delta y^2)/L_{H_\rho}^2 + \Delta z^2/L_{Z_\rho}^2]^{1/2}\} \qquad \text{(A-37)}$$

$$R(T) = \exp\{-[(\Delta x^2 + \Delta y^2)/L_{H_T} + \Delta z^2/L_{Z_T}^2]^{1/2}\} \qquad \text{(A-38)}$$

$$R(u) = \exp\{-[(\Delta x^2 + \Delta y^2)/L_{H_u}^2 + \Delta z^2/L_{z_u}^2]^{1/2}\}. \qquad \text{(A-39)}$$

In the GRAM-MOD 3 report, equations for the coefficients C, D, E, and I (A-28 through A-34) had errors, corrected above. The implementation of the relations in the GRAM program code was, however, correct.

APPENDIX B

PROGRAM MODIFICATIONS FOR THE GLOBAL REFERENCE ATMOSPHERIC MODEL (GRAM)

Line numbers are as in listing in Appendix D of the Global Reference Atmospheric Model (GRAM) MOD 3 report (Justus, et al., 1980). Line numbers followed by a letter (e.g. GRAM 95B) indicate new lines to be inserted after the indicated number (i.e. between GRAM 95 and GRAM 96). Line numbers without a following letter indicate a modified line, with the change(s) made in the line indicated by underlining. Overstriking indicates a line which is to be removed.

	Statement	Line
	IF(H.GE.25.0.AND.H.LE.90.0)GO TO 195	GRAM 95B
	IF(H.GE.25.0.AND.H.LE.90.0)GO TO 80	GRAM 151B
	UC(1)=SQRT(ABS(SP(KOUNT,1)))	ADJU 22
	VC(1)=SQRT(ABS(SD(KOUNT,1)))	ADJU 23
	WC(1)=SQRT(ABS(ST(KOUNT,1)))	ADJU 24
	UC(I)=SQRT(ABS(SP(KOUNT,I)))	ADJU 26
	VC(I)=SQRT(ABS(SD(KOUNT,I)))	ADJU 27
5	WC(I)=SQRT(ABS(ST(KOUNT,I)))	ADJU 28
	UC(1)=SQRT(ABS(U(1)+X(1)*(1.+PQ(1))/AW))	ADJU 79
	VC(1)=SQRT(ABS(V(1)-X(1)*PQ(1)/BW))	ADJU 80
	WC(1)=SQRT(ABS(W(1)+X(1)*PQ(1)/CW))	ADJU 81
	UC(N)=SQRT(ABS(U(N)-X(I2)*(1.-QQ(NM))/AW))	ADJU 85
	VC(N)=SQRT(ABS(V(N)-X(I2)*QQ(NM)/BW))	ADJU 86
	WC(N)=SQRT(ABS(W(N)+X(I2)*QQ(NM)/CW))	ADJU 87
	COMMON/WINCOM/DGH,FCORY,DX5,DY5,DUMMY(17)	CHEC 3
	IF(SD1*ST1*SD2*ST2*RD*RT*RV.GT.0.)GO TO 5	CORL 3
	~~IF(ABS(TD1).LE.0.)TD1=-0.001~~	~~CORL 13~~

```
      IF(ABS(TD1).LE.0.) TD1 = 0.001                                 CORL  23B
      IF(ABS(TD2).LE.0.) TD2 = 0.001                                 CORL  23C
      D=(RT*ST2 - C*ST1)/(A*TD1*SD1)                                 CORL  27
      COMMON/ADJCOM/A(26,3), B(26), X(26), KOUNT                     DIAG   8
C-----FAIRED-PRESSURE-----------------------------------------------FAIR--15
------P-=-EXP(ALOG(PG)*CZI-+-ALOG(PJ)*SZI)--------------------------FAIR--16
C     FAIRED GAS CONSTANT                                            FAIR  18B
      RG = PG/(DG*TG)                                                FAIR  18C
      RJ = PJ/(RJ*TJ)                                                FAIR  18D
      R = CZI*RG + SZI*RJ                                            FAIR  18E
      P = R*D*T                                                      FAIR  18F
 190  IF(LONO.GE.360)LONO = LONO - 360                               GEN4  78
      IF(LATO.GT.75)LATO = 75                                        GEN4  78B
      GLAT(J) = LATO + DLI*(J-I)                                     GEN4  86
C     COMPUTE PERTURBATIONS TO GROVES MODEL                          GEN4 148B
C-----COMPUTE-PERTURBATIONS-TO-GROVES-MODEL-------------------------GEN4-150
     $ SR(16,26),ST(16,26),DU1,DU2,DUMMY                             GRID   5
      COMMON /PDTCOM/ IT,MONTH,DUMMY1(8118)                          GRID   6
      COMMON /IOTEMP/ IOTEM1,IOTEM2,DUMMY2(62)                       GRID  17
 39   I = IREAD(IRN,1)                                               GRID 137B
      J = IREAD(IRN,2)                                               GRID 137C
 __   WRITE(6,40)JT,IRC,IREAD(IRN,3),MP,MONTH,IP,I,J,IRN,M,L GRID 138
      COMMON/WINCOM/DGH,FCORY,DX5,DY5,DUMMY(17)                      GROU   5
      IF(ABS(DINX).LE.0.) GO TO 225                                  GROU  28B
      IF(ABS(DINY).LE.0.) GO TO 250                                  GROU  35B
```

```
     $ NSAME,DUMMY2(55)                                              INTER4   4
      COMMON /C4/ GLAT(16),GLON(16),NG,DUMMY(2499)                   INTER4  10
     $ IHR,MIN,NMORE,DX,HL,VL,DZ,DUMMY(24)                           JAC      5
     $ IHR,MIN,NMORE,DX,HL,VL,DZ,DUMMY(24)                           JACH     6
      COMMON/WINCOM/ DUM(11),T,DUMMY2(9)                             PERT    13
      DPHI = (90. - ABS(CLAT)/0.017453293)**2                        PERT    23
60    RDL=SQRT(HLL+(DZ/VDL)**2)                                      PERT    51
      IF(P2.LT.-0.9)P2 = -0.9                                        PERT   89B
      IF(D2.LT.-0.9)D2 = -0.9                                        PERT   89C
      IF(T2.LT.-0.9)T2 = -0.9                                        PERT   89D
     $  IHR,MIN,NMORE,DX,HL,VL,DZ,DUMMY2(24)                         QBOG     8
     $ ,PA,DA,TA,UA,VA,IOPQ,DUMMY(2250)                              QBOG    15
     $   IHR,MIN,NMORE,DX,HL,VL,DZ,B,EPS,IOPP,LOOK,IET,GLAT,         RIG      5
      COMMON/IOTEMP/IOTEM1,IOTEM2,IUG,DUMMY(61)                      RTRA     2
      IF(NPOP.EQ.0)GO TO 830                                         SCIM  468B
      COMMON/C4/XL(16),YL(16),NP,DUMMY(2499)                         SELE     3
      COMMON /IOTEMP/ IOTEM1,IOTEM2,DUMMY2(62)                       SELE     8
      IF(LO.LT.0)LO = LO + 3600                                      SELE   34B
      YEL = YL(II)                                                   SELE   43B
      IF(YEL.LT.0.)YEL = YEL + 360.                                  SELE   43C
      EL = (350. - YEL)*DEGRAD                                       SELE    44
      IF(L2.LT.0)L2 = L2 + 360                                       SELE   84B
      IF(L2.LT.0)L2 = L2 + 360                                       SELE  108B
      IF (IL(K1).NE.0) GO TO 100                                     SELE   123
      RPSCALE = 1.0                                                  SETU   53B
```

```
      READ(5,10)RP1L,RP1S,RD1L,RD1S,RT1L,RT1S,RU1L,RU1S,RV1L,SETU  68
     & RV1S,RPSCALE                                              SETU  68B
      IF (RPSCALE.LT.0.0.OR.RPSCALE.GT.2.0)RPSCALE=1.0           SETU  68C
      PR(IHR,K) = (IP(J)*RPSCALE/1000.0)**2                      SETU 227
      DR(IHR,K) = (ID(J)*RPSCALE/1000.0)**2                      SETU 228
420   TR(IHR,K) = (IT(J)*RPSCALE/1000.0)**2                      SETU 229
      UR(IHR,K) = (IP(J)*RPSCALE)**2                             SETU 282
485   VR(IHR,K) = (ID(J)*RPSCALE)**2                             SETU 283
600   DO 610 I = 1,17                                            SETU 484
      WRITE(6,9870)RPSCALE                                       SETU 544B
9870  FORMAT(/"  RANDOM PERTURBATION SCALING FACTOR = ",F7.3)SETU 592B
     $  IHR,MIN,NMORE,DX,HL,VL,DZ,DUMMY2(24)                     TINF   5
     $  IHR,MIN,NMORE,DX,HL,VL,DZ,DUMMY2(24)                     TME    6
     $THETR,DUM3(15),FLAT,DUMMY(18)                              WIND   5
      ABSPHI = ABS(PHIR)                                         WIND   7
      IF(ABSPHI.LT.0.017453293*FLAT)GO TO 40                     WIND   7B
      IF(RHO.GT.0..AND.T.GT.0.0.AND.ABS(FCORY).GT.0.)GOTO 20 WIND   8
      DU = 0.0                                                   WIND  10B
      DV = 0.0                                                   WIND  10C
      IF(ABS(FCORY).LE.0.)GO TO 31                               WIND  11
      IF(ABSPHI.GE.0.017453293*FLAT)RETURN                       WIND  19
40    CONTINUE                                                   WIND  19B
      IF(H.GT.20.0.AND.H.LT.95.0)GO TO 99                        WIND  23B
      IF(IH.LT.25)GOTO 130                                       WIND  27
      DU = FACG*DU + FACS*DUS                                    WIND  47B
      DV = FACG*DV + FACS*DVS                                    WIND  47C
```

These program changes (in GRID4D, GROUP, SELEC4, and WIND subroutines) should correct several problems which have been encountered by GRAM users, especially at low altitudes and low latitudes (and near zero longitude). Unreasonably large winds can still result, however, at altitudes below 25 km, where the spherical harmonic wind model does not apply, and where the pressure data on the 4-D data tapes can result in erroneously large horizontal gradients, on which the geostrophic winds are based. Other changes (in subroutine ADJUST) help avoid square roots of negative numbers, resulting from missing or unreasonable standard deviation values which might be in some records on the 4-D data tapes.

The Groves-Jacchia fairing process has been modified (FAIR 18B - 18F) to interpolate on the gas constant, consistent with interpolation processes used elsewhere in the program. Density "spikes" which have been reported in this height region, however, may persist as the result of differences in values of density (and vertical density gradient) which can occur between the Groves and the Jacchia models (especially when represented at percent deviations from the U.S. Standard, which can have an even different vertical gradient). Any cases of density "spikes" of more than a few percent should be reported to NASA Marshall Space Flight Center, with details of the input parameters which produced this condition.

These changes include a new input parameter, RPSCALE (in subroutine SETUP), the random perturbation scaling factor, which can take on legal values between 0 and 2, and will modify the random perturbation standard deviations proportionally. This parameter value is to be input at the end of (optional) line 3, if a value other than the default value of 1.0 is desired. Changes in subroutine PERTRB should improve the random perturbation simulation values. However, the phenomenon of increasing vertical gradient magnitudes with decreasing vertical step size is an inherent feature of the Markov-chain random perturbation model (see detailed discussion in the text). Gradient magnitudes should have realistic values for vertical step sizes of about 1 km or greater, but can take on unrealistically large values if vertical step sizes of less than 1 km are used. Hence, it is recommended that 1 km be used as a minimum vertical step size.

Changes are also included which add sufficient dummy parameters to all COMMON block definitions so that there sizes will be consistent among all of the subroutines.